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Status Report

Covering period August 1, 1982 to January 31, 1983

under NASA Research Grant NAG-1-129

on

AEROACOUSTICS OF A POROUS PLUG SUPERSONIC JET NOISE SUPPRESSOR

by

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The analytical and experimental investigation of the aeroacoustics of a porous-plug supersonic jet noise suppressor was initiated on January 1, 1981 under the NASA (Langley Research Center) grant #NAG-1-129 to Syracuse University. The needed modifications of the existing multistream coaxial jet-rig; the compressed air facility and pressure controls; the design, the fabrication and the installation of the new plenum-chamber for plug-nozzle and the design and the machining of the first contoured plug-nozzle were completed by December 31, 1981. The research accomplishments over the period January 1, 1981 to July 31, 1982 were detailed in the previous status report[1]. The optical and the aeroacoustic data of the contoured plug-nozzles and of the conical convergent nozzle alone were discussed therein.

The research accomplishments of the period August 1, 1982 to December 31, 1982 are discussed in this progress report. In summary, these accomplishments are as follows:

<u>The Accomplishments Covering the Period August 1, 1982 to September 30, 1982</u>*

The experimental investigations reported in Ref. 1 were continued. The optical and acoustic studies were conducted on a conical plug-nozzle for a range of pressure ratios ξ=1.81 to 3.67. A conical plug with plug-nozzle throat area and the ratio of the plug to nozzle radius at the throat equal to those acoustic studies were conducted on a conical plug-nozzle for a range of pressure ratio ξ = 1.81 to 3.67. A conical plug with plug-nozzle throat area and the ratio of the plug to nozzle radius at the nozzle throat equal to those of the isentropic plug-nozzle, i.e. the plug No. 2 of Ref. 1**, was selected. Both the pressure ratio and the mass flow rate for the conical and the isentropic plug nozzle flows were matched. The semi-angle of the conical plug was

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* These were discussed in detail in the unsolicited research proposal submitted to NASA for additional support for the period January 1, 1983 to May 31, 1983 (Ref.2).

** The plug No. 1 was contoured on the basis of two-dimensional planar flow. The coordinates of the plug Nos. 1& 2 were listed in table on p.21 of Ref. 1. Due to typographical error the numbering of the plugs at the top of the table were interchanged.

so chosen that its surface area equals that of the isentropic plug. It may be noted that this selection criterion led to a conical plug geometrically not much different from the nearly isentropic (contoured) plug. The two plugs are shown in Fig. 1 where their dimensions are tabulated. The optical and the acoustic results of the tests are summarized below.

Optical Results

The salient flow features (flow divergence, jet flow boundary shape, etc) and the shock structures are compared in a few typical shadowgraphs of the conical plug-nozzle flows (Fig. 2) with those obtained earlier for the contoured plug-nozzle and for the convergent-nozzle alone (lip angle $\alpha = 11.91^{o}$ corresponding to a fully expanded jet flow exit Mach number $M_e = 1.5$). The contoured plug-nozzle flow is reasonably free of shock structure at an operating pressure ratio $\xi = 3.04$. Moreover, the free jet boundary is nearly horizontal and straight at the nozzle exit. Therefore, at this operating pressure ratio the flow is nearly isentropic. The shock (see (d) in Fig. 2 , B: $\xi = 3.04$) is too weak to sustain, on subsequent reflections, a cellular shock structure farther downstream. The comparison of the optical data at $\xi = 3.67$ of under-expanded jet flows with and without the contoured plug shows much weaker shocks in the contoured plug-nozzle flow (Fig. 2).

At $\xi = 3.04$, the pressure ratio for which the flow is reasonably isentropic over the contoured plug, repetitive cellular shocks in flow past the conical plug have been observed. At higher pressure ratios (off-design for the isentropic plug), the flow features and shock structure are nearly similar for both the isentropic and the conical plug-nozzle flows.

Acoustic Results

One-third octave sound pressure levels were recently recorded for a conical plug-nozzle in an anechoic chamber at eight azimuthal positions from 15° to 120° measured with reference to the downstream jet axis on an arc of 10 ft. from the nozzle exit in a horizontal plane containing the nozzle axis and the axis perpendicular to the microphone diaphragm. These acoustic data for the conical plug and the earlier acoustic data for the isentropic plug-nozzle and the convergent nozzle alone (i.e. the nozzle without the plug having throat area 18% larger than that of the isentropic plug-nozzle No.2) have been analysed and compared. The acoustic results are presented in Fig.3.

The acoustic power level spectra for the convergent nozzle alone, isentropic plug-nozzle and the conical plug-nozzle operated at the design pressure ratio of the isentropic plug-nozzle are presented in Fig. 3(a). The convergent nozzle spectra shows sharp peaks at high frequencies which are likely due to shock associated noise. No such peaks are observed in the isentropic plug-nozzle spectra. This result is supported by optical data, Fig. 2, where the isentropic plug-nozzle at $\xi = 3.04$ shows a nearly isentropic flow while the convergent nozzle flow shows cellular shock structure. The directivity plot, Fig. 3(b), shows the isentropic plug-nozzle has significant noise reductions as high as 9dB at $\theta = 30^\circ$, $\theta = 90^\circ$ and $\theta = 120^\circ$, compared to the convergent nozzle. Hence, both the mixing noise predominant at small angles (θ=30°) from the jet axis and shock-associated noise, a significant noise source at larger angles (θ=90° & 120°), are modified substantially by the use of the isentropic plug-nozzle at its design pressure ratio. Also, the conical plug-nozzle (which was designed on the basis of the same K and the same surface area as those of the isentropic plug-nozzle) has the shock-associated noise level about 3 to 4 dB higher than that of the isentropic plug-nozzle, Fig. 3(c) presents acoustic

efficiency (η = acoustic power/mechanical power) of the isentropic plug-nozzle for ξ = 1.81 to 3.67 and those of the conical plug-nozzle and of the convergent nozzle alone at ξ = 3.04. The acoustic efficiency of the isentropic plug-nozzle is found to be lower than those of the convergent nozzle alone and the conical plug-nozzle at ξ = 3.04.

For the conical plug-nozzle flow, the increase in acoustic power levels and in the overall sound pressure levels are not appreciable when compared to the isentropic plug-nozzle. This is because the geometries of the two plugs are not very different (see Fig. 1). Both the plugs have the same throat area, the same surface area and the same K (ratio of the plug radius at the throat to that of the nozzle). The acoustic efficiency of the conical plug-nozzle is found to be only a little higher than that of the nearly isentropic plug-nozzle at the design pressure ratio. Thus, the aerodynamic and aeroacoustic performances of a solid conical plug-nozzle are nearly equivalent to the performances of an isentropic contoured plug-nozzle if the solid conical plug is designed on the basis of the same radius ratio K and the same surface area as those of the isentropic plug.

For an isentropic externally expanded plug-nozzle, the radius ratio K is fixed for a given fully expanded jet flow Mach number M_e at the plug-exit and the maximum length is fixed for the given M_e and R_N, radius of the nozzle-lip. Then, as compared to the isentropic plug, a conical plug with a larger K but having the same length will lead to the formation of two sets of much stronger repetitive shock structures in the flow downstream of the plug exit due to over-expansion of the flow on the conical plug surface (for identification of these two sets of shock structure see sketch (a) in Fig.4). Such is

also the case if the conical plug has the same K but a smaller length as compared to the isentropic plug but in this case the shock formation due to the unintercepted expansion waves would be stronger. This will result in a higher level of radiated noise. Again, if the choice be a conical plug of the same K but of longer length as compared to the isentropic plug, the oblique shock structure formed by compression waves from the outer jet flow boundary may be incident on the plug surface. This might result not only in a deterioration of the accustic performance but in loss of thrust as well. Thus, if practical design considerations demand a higher value of K (0.6-0.9) or a longer length for the conical plug having a higher design pressure ratio (say in the range of 3.0 to 5.0), the plug-nozzle flow with stronger shock structure may result which warrants some modifications of the cellular shock structures for improved aeroacoustic performance. It was decided to study first a conical plug of longer length but of the same K as compared to the isentropic plug, for possible choice for studying the effects of perforations on the favorable modifications of the shocks in the conical plug-nozzle flows.

Investigations During the Period September 30, 1982 to December 31, 1982.

1. Optical studies were conducted on a conical plug having a length 25% larger and the same K as for the isentropic plug (pressure ratio = 3.04). The shock structures in the plug nozzle flows were observed to be not much pronounced. The acoustic data for this plug have been collected for a range of pressure ratio and these are being analyzed. If this conical plug nozzle has an acoustic performance much different from that of the corresponding isentropic plug nozzle, the effect of porosity of the conical plug on the aero-acoustics of the plug-nozzle flows will be studied. If such be not the case

the conical plugs designed for larger values of K are to be tested.

2. A backward marching method-of-characteristics solution for the contour of the plug was completed on the basis of a uniform axial flow at the plug exit. The contoured plug thus obtained has the geometrical configuration ratio K of 0.54 and the design pressure ratio of 3.67. The optical studies conducted on the new contoured plug did not reveal an exit flow totally free of shock structures though the only conical shock in the flow was so weak that it did not repeat itself i.e., there was no evidence of repetitive cellular shock structures in the exit flow. The source of the conical shock was noted to be the sonic region of the plug-nozzle flow. The entry flow is essentially nonuniform and converging at the throat of such a plug nozzle having different slopes of the inner and the outer walls. A precise design of the sonic region, as is well known, is necessary for obtaining a truly isentropic flow. This is all the more important for an isentropic plug-nozzle which, being a minimum length nozzle, require the right location of the sonic line in order that the expansion waves are all centered at the lip of the nozzle. The literature available on the transonic flow analyses does not provide criteria for precisely establishing the sonic region for such a throat configuration as that of an isentropic contoured plug-nozzle. For an isentropic plug-nozzle the slope of the inner wall and the geometrical configuration factor K are not known a priori for a prescribed design exit Mach number. In fact, in order to alleviate these difficulties only a backward-marching method-of-characteristic solution for obtaining the isentropic plug contour was preferred to the usual forward-marching MOC solution which require a precise specification of a fully supersonic initial value line.

3. A forward marching method-of-characteristics solution has now been developed for prediction of plug-nozzle flow field for any prescribed shape of the plug, may these be conical or contoured.

Presentation of a Paper

A paper entitled, "Aeroacoustics of a Supersonic Porous Plug-Nozzle Jet Noise Suppressor", has been accepted for presentation at the 8th AIAA Aero-acoustics Conference to be held in April 1983. We expect to include in the paper a summary of the aeroacoustic results on the contoured plug, solid conical plug and the porous conical plug.

Planned Studies up to May 15, 1983

1. Two solid conical plugs (one having shocks, generated by reflections of expansion waves from the free jet boundary as compressions, incident on the plug surface and the other having shocks standing downstream of the plug apex: see sketches (b) and (c) in Fig. 4 will be selected. Many geometrical configurations are possible which may result in such shock patterns in the conical plug-nozzle flow. Analysis will be carried out to select a solid conical plug of preferred geometry and minimum thrust penalty. The optical and aero-acoustic data will be recorded for these solid conical plugs.

2. The characteristic solution will be extended to predict the flow past the porous surface of the conical plug of a selected half-angle and length. The related boundary conditions and the problems of modeling of the porous plug-nozzle flows were noted in the earlier report[2]. It is proposed that the perforations be considered as discrete rings of continuous hole on the plug surface. By this simplification, the flow over the porous plug surface may be considered axisymmetric with the p- and θ- condition applied alternately along the porous

plug surface. The flow model, thus modified, becomes more amenable to a theoretical analysis using method of characteristics for irrotational flows. Such a characteristic solution is to be initiated by considering first only one ring of continuous hole provided around the plug surface. The flow and the shock modifications in the otherwise solid conical plug-nozzle flow will be predicted.

3. A set of spark shadowgraphic and acoustic data will be recorded for a porous conical plug-nozzle at the optimized deisgn and operating conditions as deduced from (2) above. The perforations may be uniformly distributed over the whole of the plug surface or they may be confined to discrete axial locations on plug surface selected to optimize the weakening of the shock structure present in the corresponding solid conical plug-nozzle flow.

4. Observations of shock structure, flow boundary, etc., for the isentropic plug-nozzle and the conical plug-nozzle flows will be compared with the theoretically predicted values. With these comparisons as a guide, the modifications as needed in the theoretical model of the porous plug-nozzle flows will be considered. These comparisons of the aerodynamic and the aeroacoustic data will be helpful in understanding and assessing the role of porosity in supersonic plug-nozzle jet noise suppression.

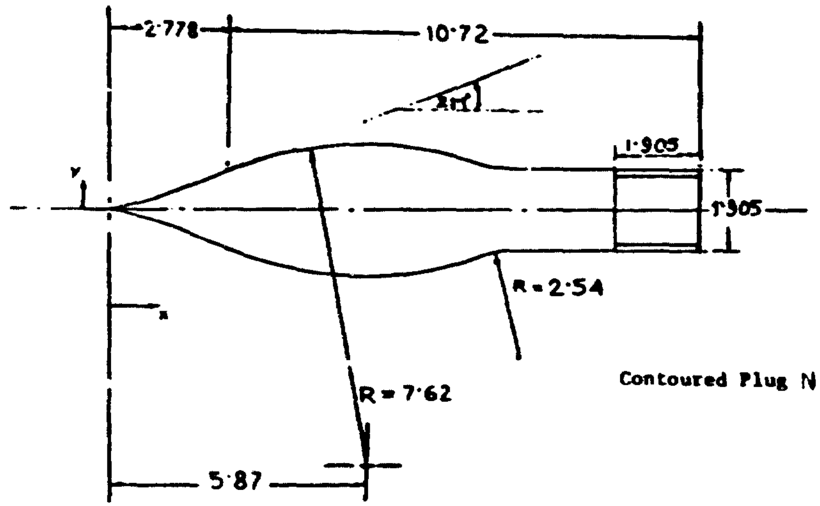
5. The aeroacoustic studies on the lines as proposed above are to be continued beyond the current date of expiration of the project, i.e. May 15, 1983, by the graduate student working on the problem for his Ph.D. dissertation.

REFERENCES

1. Dosanjh, D.S., Matambo, T.J. and Das, I.S., "Aeroacoustics of a Porous Plug Supersonic Jet Noise Suppressor", Status Report covering period January 1, 1981 to July 31, 1982, submitted to NASA Langley Research Center, under NASA Research Grant NAG-1-129, August 1982.

2. Dosanjh, D.S., "Aeroacoustics of a Porous Plug Supersonic Jet Noise Suppressor", an Unsolicited Research Proposal for Additional Support under NASA Research grant NAG-1-129, for the period January 1, 1983 to May 31, 1983, to NASA Langley Research Center, December 1982.

3. Das, I.S., Matambo, T.J. and Dosanjh, D.S., "Aeroacoustics of a Supersonic Porous Plug-Nozzle Jet Noise-Suppressor," accepted for presentation for AIAA 8th Aeroacoustic Conference, Atlanta, Georgia, April 1983.

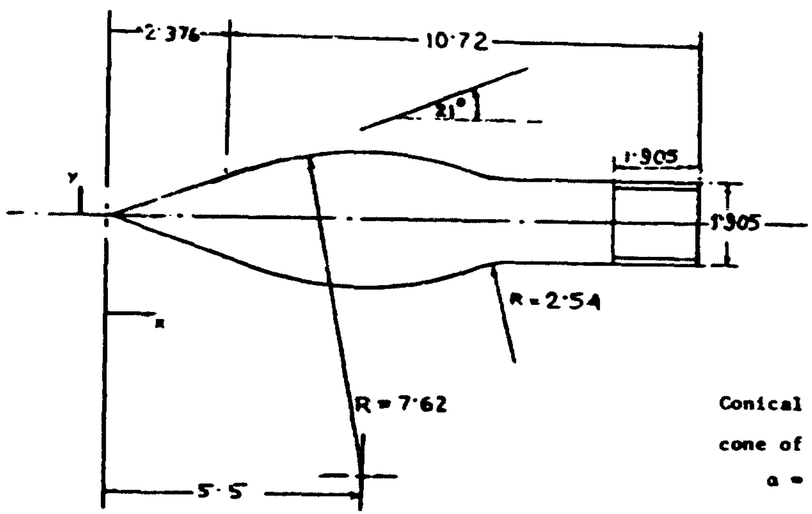


Contoured Plug No.2

R_N = 2.225 (Nozzle Radius)

K = .41 (R_p/R_N)

R_p = .912 Radius of Plug at the throat



Conical Plug

cone of semiangle

α = 21°

Fig. 1 Isentropic and Conical Plug Geometry

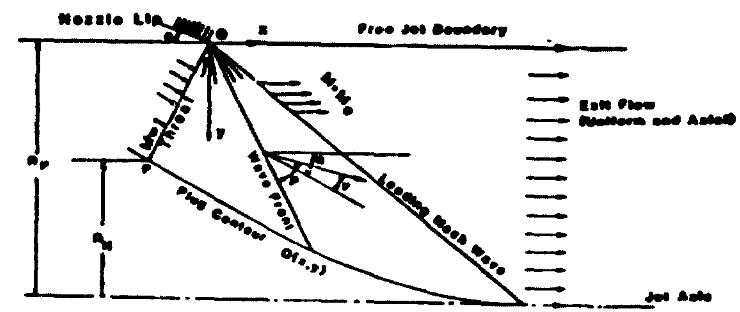


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TABLE: PLUG COORDINATES IN CMS.*

X	Y: PLUG NO.1	Y: PLUG NO.2	Y: CONICAL PLUG
-0.277	1.846	1.313	1.313
-0.010	1.925	1.415	1.415
0.112	1.960	1.463	1.462
0.214	1.986	1.503	1.501
0.306	2.009	1.540	1.537
0.394	2.030	1.574	1.571
0.479	2.049	1.607	1.603
0.563	2.067	1.639	1.635
0.647	2.083	1.671	1.668
0.731	2.098	1.702	1.700
0.816	2.113	1.733	1.733
0.903	2.126	1.764	1.766
0.992	2.139	1.796	1.800
1.083	2.151	1.827	1.835
1.177	2.162	1.858	1.871
1.274	2.172	1.890	1.908
1.374	2.181	1.922	1.947
1.478	2.190	1.954	1.987
1.586	2.198	1.986	2.028
1.698	2.204	2.019	2.072
1.816	2.210	2.052	2.117
1.938	2.215	2.086	2.163
2.066	2.219	2.120	2.213
2.200	2.222	2.155	–
2.340	2.224	2.190	–
2.488	2.225	2.225	–

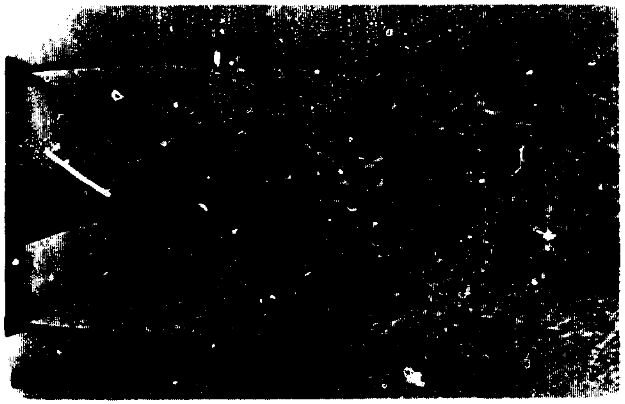
*In Ref.1 the dimensions of Plug Nos. 1 & 2 got interchanged due to typographical mistake.

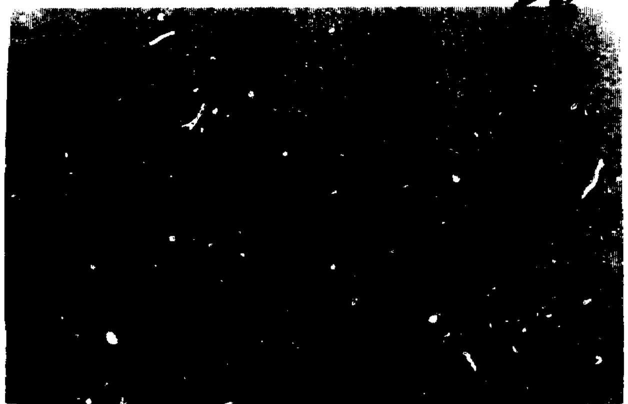
A: [illegible]
(a) Repetitive shocks
(b) Strong compression waves
(c) Branch of lambda shock

B: [illegible]
(d) [illegible] plug surface reflections
(e) Weak shock due to expansion waves not intercepted by plug

C

A: ξ=3.67
(f) Mach disc
(g) Slip surface





(h) Wake from plug tip

Fig. 2. Typical Spark Shadowgraghs of Supersonic Jet Flows from:

(A) Conical Convergent Nozzle
(B) Contoured Plug-Nozzle
(C) Conical Plug-Nozzle

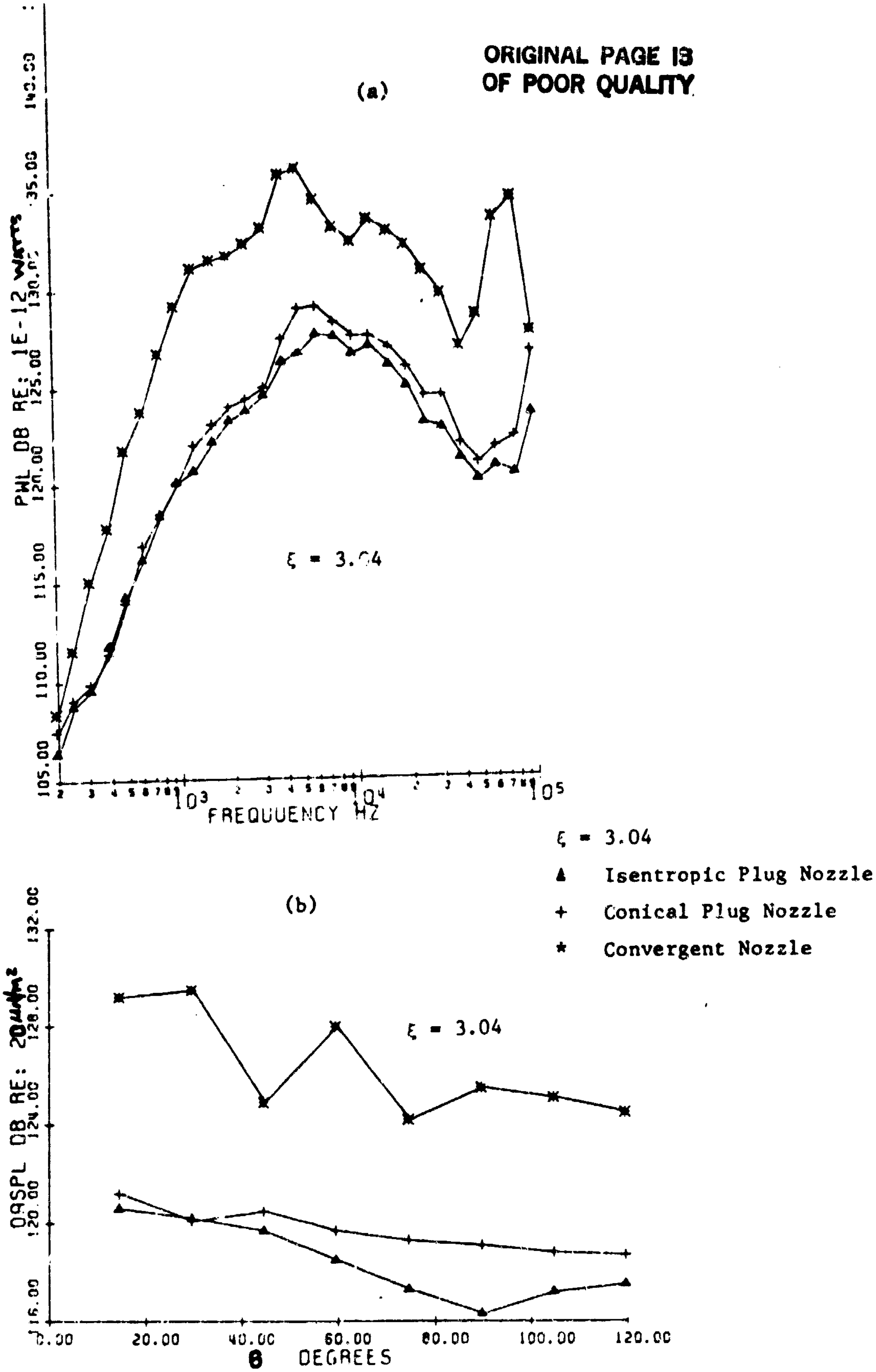


Fig. 3. Comparisons of Acoustic Performance of an Isentropic Plug-Nozzle, Conical Plug-Nozzle and Convergent Nozzle alone.

(a) Acoustic Power Spectra
(b) Overall Sound Spectra Level
(c) Acoustic Efficiency

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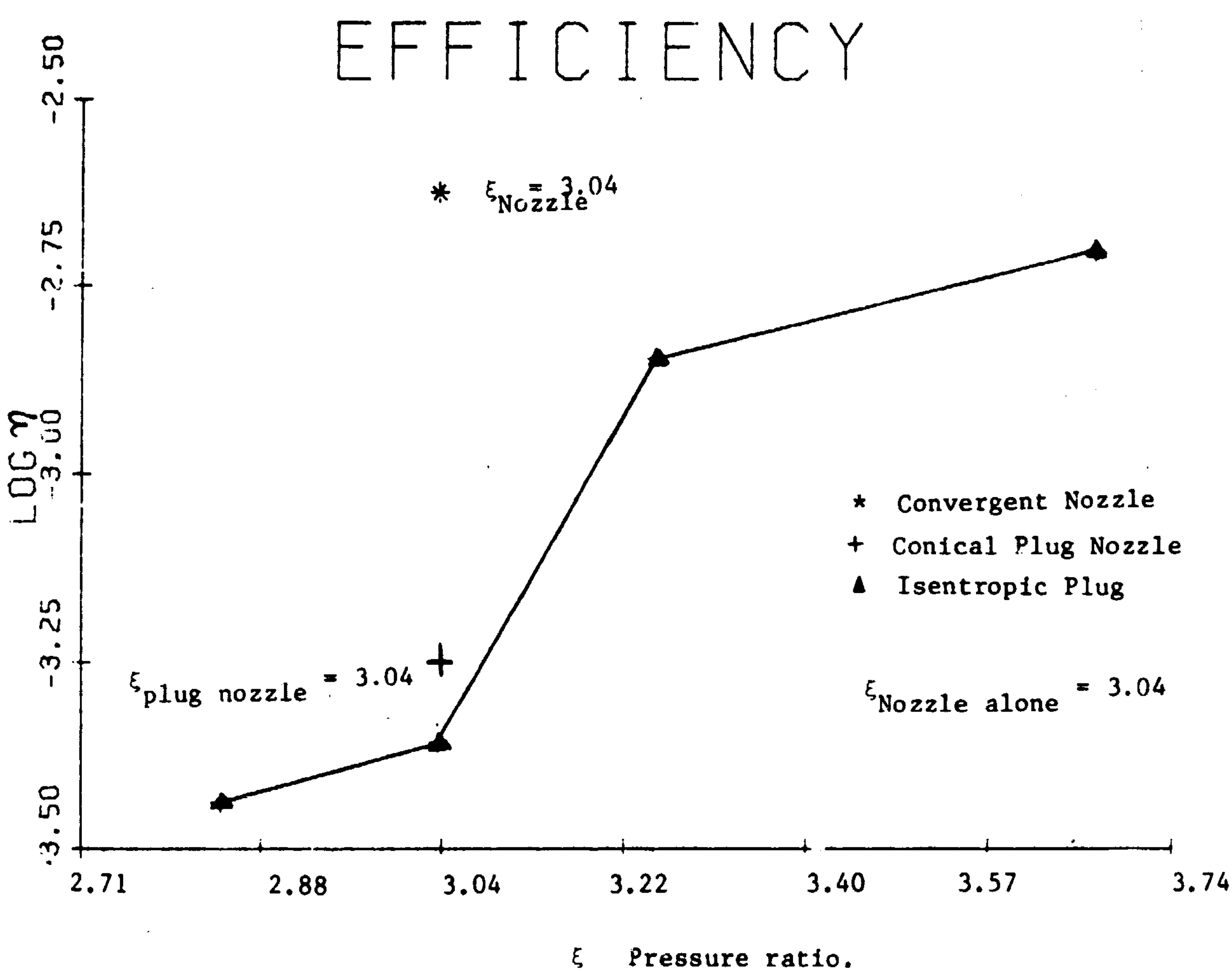
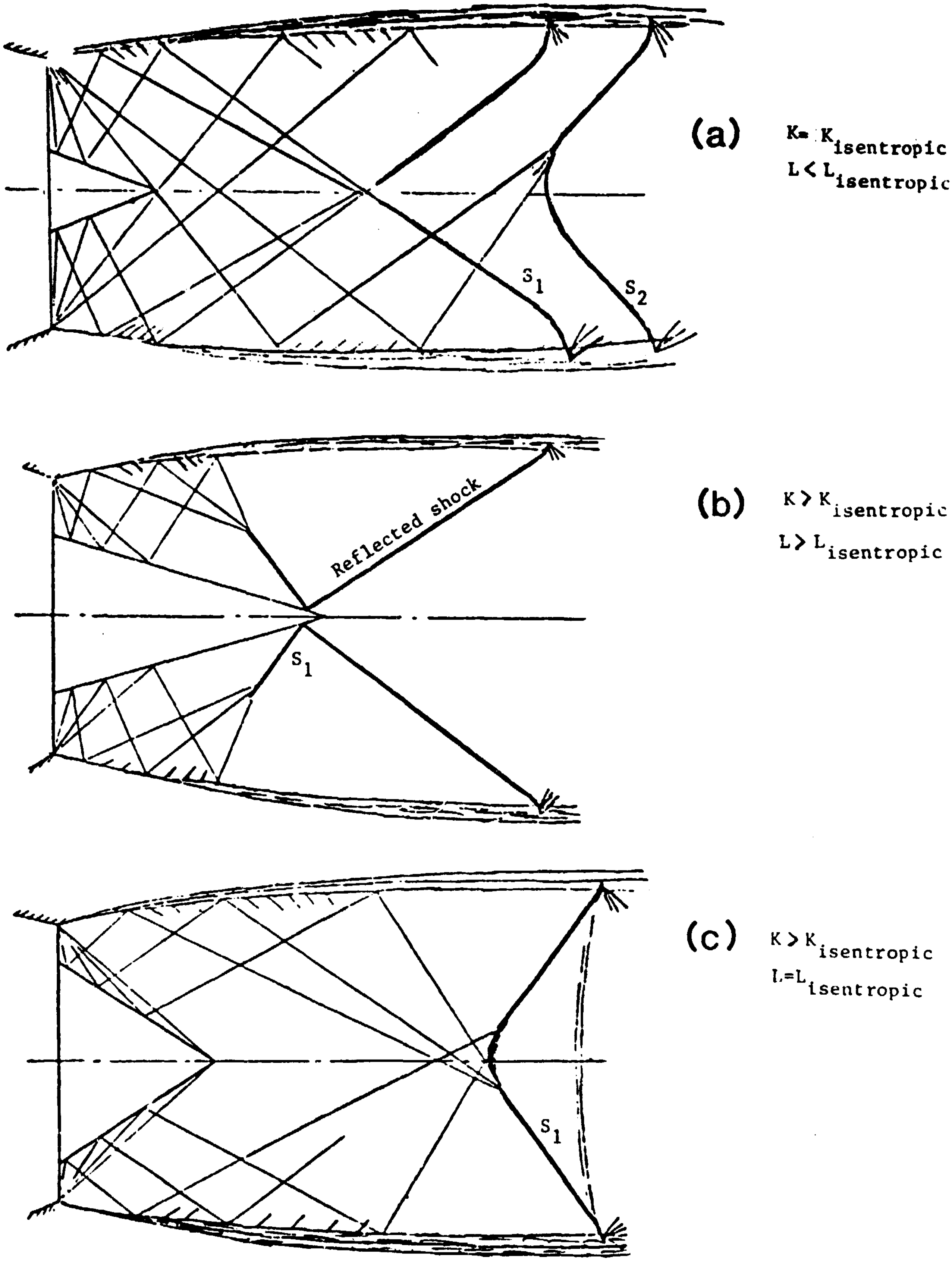
Fig. 3 Cont'd

(c)





S_1: shock related to reflection of expansion waves from the plug surface

S_2: shock due to reflection of expansion waves not intercepted by the plug surface

FIG 4 WAVE STRUCTURE IN FLOWS PAST CONICAL PLUGS AT THE SAME PRESSURE RATIO